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Experimental and analytical investigation of the inelastic behavior of structures isolated using friction pendulum bearings

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Abstract

Current American and European code provisions prohibit yielding of base-isolated structures. Therefore, the majority of existing base-isolated structures are designed elastically. This study aims at investigating the necessity of the elastic design of these structures through the analytical and experimental investigation of their inelastic behavior.

This analytical investigation is performed using a two-degree-of-freedom model of a base-isolated structure. The bilinear hysteretic behavior of the structure and the isolator is simulated via a Bouc-Wen model. Numerous simulations of the response to strong ground motion excitations were performed using Matlab and Opensees models.

The experimental investigation performed in this study is based on the response of a reduced-scale base-isolated steel structure to strong recorded ground motion accelerations applied using the shaking table of the IBK Structural Testing laboratory of ETH Zurich. The part of the structure designed to develop inelastic behavior is a pair of steel coupons that can be easily replaced after such damage. The structure is base-isolated using four friction pendulum bearings provided by MAGEBA.

The experimentally observed inelastic behavior of base-isolated structures is compared to the analytically simulated behavior. A relation between experimentally obtained strength and displacement ductility of these structures is presented. The influence of a wide range of response parameters is quantified and presented. The experimentally obtained data is compared to an analytically derived strength-ductility-period relation for seismically isolated structures. This comparison serves to validate the proposed analytical relation and to increase the understanding of the behavior of inelastic seismically isolated structures.

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Keywords: Experimental investigation of inelastic base-isolated structures; Inelastic seismically isolated structures

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1. Introduction

Numerous researchers have investigated the behavior of a wide variety of seismic isolation bearings analytically [1-4] and experimentally [5-6] to determine the response of the designed base-isolated structures subjected to different types of ground motion excitation [7]. In most of these studies, the isolated superstructures are designed to respond elastically when subjected to the design ground motion level.

The response of base-isolated structures when the superstructure enters the inelastic behavior range is less well understood. Such inelastic behavior of base-isolated structures is not only theoretical, but can occur in two cases. First, the seismic forces acting on an existing base-isolated superstructure could exceed the design forces due to, for example, a ground motion stronger than the design ground motion level, or unintentional construction of a weak superstructure. Second, the base-isolated superstructure may be intentionally designed to enter its inelastic response range for design-basis ground motions to reduce their cost and thereby offset the cost of the seismic isolation system.

Constantinou and Quarshie [8], Ordonez et al. [9], Kikuchi et al. [10], Thiravechyan et al. [11] and Cardone et al. [12] investigated the response of inelastic seismically isolated structures and agreed that allowing seismically isolated structures to yield requires careful consideration. Vassiliou et al. [13-15] concluded that designing typical seismically isolated structures to behave elastically, as prescribed by current seismic design codes, is not overly conservative but a necessity that emerges from the fundamental dynamics of such structures.

The dynamics of a base-isolated structure, following to the work of Naeim and Kelly [16], is investigated analytically using a two-degree-of-freedom (2-DOF) in-plane model, presented in Fig. 1. The system consisting of the isolation bearings and the isolation base is defined as isolation system. The structure above the isolation system is defined as the isolated superstructure. Masses m_s *and* m_b represent the mass of the isolated superstructure and the mass of the base above the isolation system, respectively. The stiffness and damping are denoted as k_s, c_s, when referring to the superstructure and as k_b, c_b when referring to the base. Horizontal displacement u_s is the relative displacement of the superstructure with respect to the base and u_b is the horizontal displacement of the isolation bearings with respect to the ground. The ground displacement to which the system is subjected is denoted as u_g. The notation used to describe the inelastic response of fixed-base single-degree-of-freedom (SDOF) structures is adopted as follows.

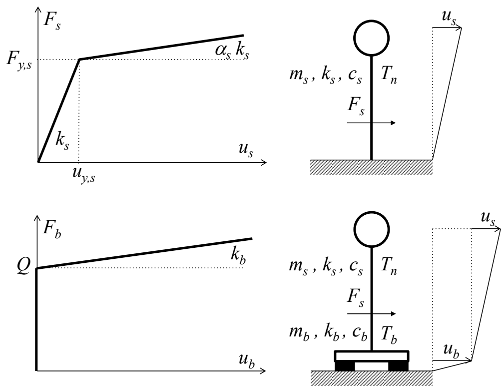

Fig. 1. Parameters of the SDOF model of a fixed-base structure and of a 2-DOF model of a base-isolated structure.

Nomenclature

R_y	Strength reduction factor defined as the ratio of the minimum strength required to maintain the SDOF system response in the elastic range, $F_{el,s}$ and the SDOF system yield strength $F_{y,s}$ ($R_y=F_{el,s}/F_{y,s}$)
μ	Displacement ductility defined as the ratio of the maximum inelastic displacement $u_{m,s}$ and the yield displacement $u_{y,s}$ ($\mu=u_{m,s}/u_{y,s}$)
T_n	Fixed-base period of the superstructure $T_n = 2\pi\sqrt{m_s / k_s}$
T_b	Isolation period of the superstructure $T_b = 2\pi\sqrt{(m_s + m_b)/k_b}$
γ_m	Mass ratio $\gamma_m = m_s/(m_s + m_b)$

2. Experimental setup for shaking table tests of a base-isolated cantilever structure

As shown in Fig. 2, a base-isolated cantilever structure with a lumped mass m_s=250 kg attached on the top was designed and built in ETH Structural Testing Laboratory. The cantilever structural system consists of two vertical steel columns, connected horizontally with 7 stiffening steel beams that guarantee the in-plane behavior of the system under shaking table excitation. The steel beams are anchored to a bottom plate. This plate is supported by two hinge elements that allow the rotation of the plate in the plane of the excitation and two steel coupons that restrain this rotation. These four elements are anchored to another plate, which is supported by the base plate of the isolation system with mass m_b. Both plates above the base plate are equipped with small gaps that allow for the easy replacement of the steel coupons in case of damage. The isolation system consists of 4 friction pendulum bearings, which are distributed symmetrically on the shaking table.

Fig. 2. Experimental setup of the cantilever base-isolated structure in ETH Structural Testing Laboratory

The isolators are made by MAGEBA SA as a small version of their RESTON Pendulum Type Mono isolator. The fixed-base period of the constructed structure is T_n=0.52 s, as measured in a free vibration test. The post-yielding isolation period T_b=2.3 s was determined using a sine sweep shaking table excitation. The measured value of the yield strength of the isolation system is Q=520 N. The differences between the designed and the actual structure stem from the inevitable discrepancies between the nominal and the actual mechanical properties of the components. The mass ratio of the constructed structure is γ_m=0.2. Two different diameters have been used for the reduced-diameter middle part of the steel coupons, one of d=4 mm and one of d=5 mm.

The structure shown in Fig. 2 was excited by a group of 4 strong ground motion excitations taken from the PEER Center ground motion database [17], shown in Table 1. The goal of the tests of the isolated superstructure under these motions is to investigate its inelastic behavior and to verify the results of the analytical simulation.

Table 1. Ground motion ensemble

Earthquake	Station	Record	Scaling of the original motion
San Fernando 1971	279 Pacoima Dam	PCD164	35%
Northridge 1994	USGS/VA 637 LA-Sepulveda VA Hospital	0637-270	75%
Coalinga 1983	1651 Transmitter Hill station	D-TSM270	100%
Tabas 1978	9101	TAB-LN	32.5%

3. Experimental response to ground motion excitation and comparison with analytical simulation

3.1. Displacement time history response

The analytically and experimentally derived displacement time history response of the isolation system and the isolated superstructure due to Northridge 1994 ground motion excitation (Table 1) is shown in Fig. 3, 4 respectively.

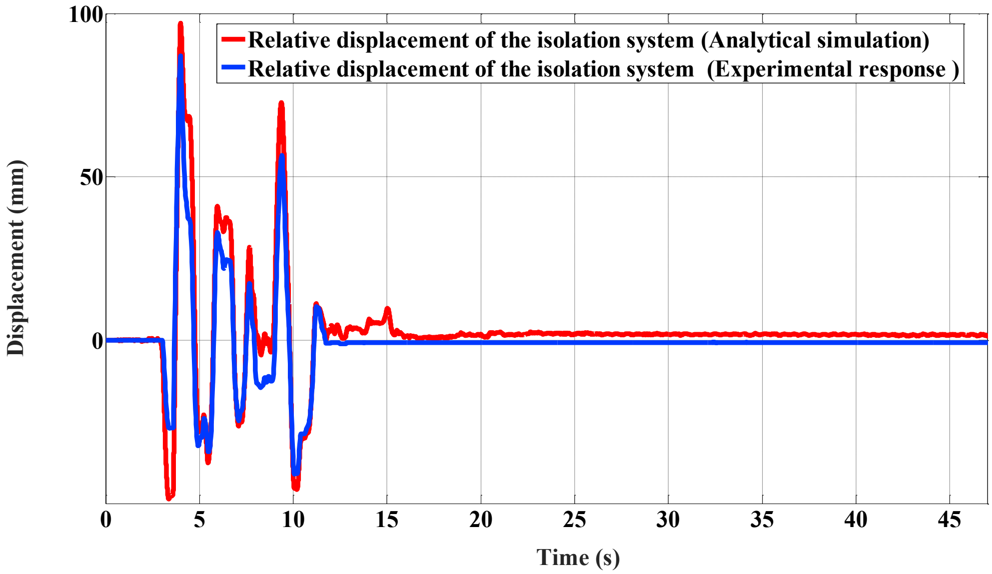

Fig. 3. Response of the specimen with 4 mm, 480 MPa coupons to the 75% 1994 Northridge ground motion excitation: displacement time history responses of the isolation system (Analytical simulation and experimental response)

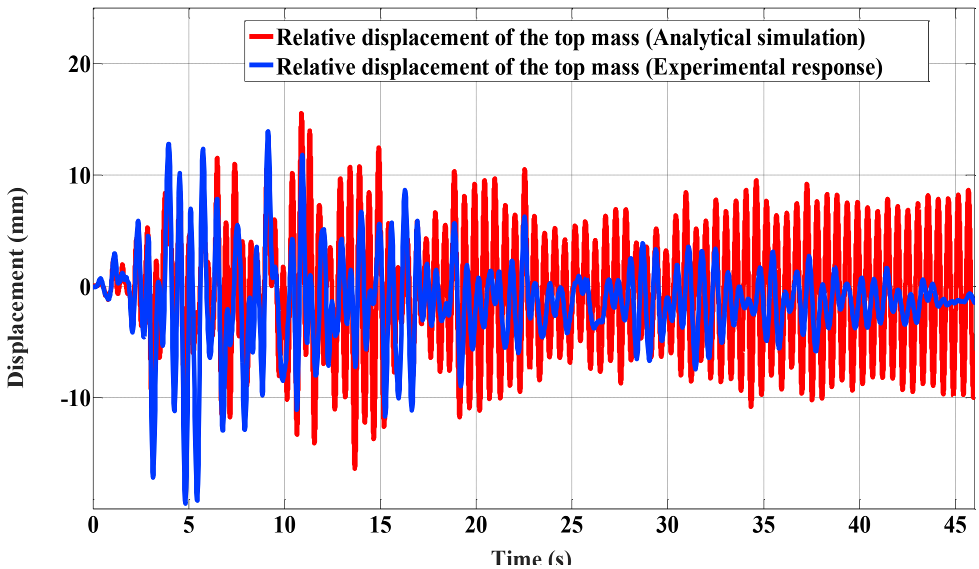

Fig. 4. Response of the specimen with 4 mm, 480 MPa coupons to the 75% 1994 Northridge ground motion excitation: displacement time history responses of the isolated superstructure (Analytical simulation and experimental response)

The experimentally derived displacement time history response of the isolation system is in good agreement with the analytically derived response. However, the maximum bearing displacement observed experimentally is 10% lower than the analytically derived value. This difference is attributed to the high value of static friction (stiction) of the constructed bearings, which led to the delayed activation of the isolation system in comparison with the analytical simulation of the activation of the bearings.

The displacement time history response of the top mass of the isolated superstructure, which was observed experimentally is similar to the analytically derived response, particularly during the activation of the isolation system (0-10 s). The discrepancies between the experimental response and the analytical simulation of the top mass are related to imperfections in the hinge, which led to unintended shear deformation of the coupons that cannot be simulated with the analytical model presented in Fig. 1.

3.2. R_y-μ-T_n relations

The relations between the strength reduction factor R_y, the displacement ductility ratio μ and the vibration period of the structure T_n have been determined by researchers in the past for fixed-base structures through bilinear [18] or trilinear [19] functions. The analytical investigation of the inelastic response of base-isolated structures subjected to a wide range of ground motion excitations has led to the determination of these relations for base-isolated structures by Tsiavos et al. [20].

The relations between R_y and μ have been determined experimentally in this study for the structure shown in Fig. 2 with a vibration period T_n=0.52 s. These R_y-μ-T_n relations are compared with the analytically derived relations for base-isolated structures with γ_m=0.2 [20], the proposed trilinear relations for base-isolated structures with γ_m=0.9 [20] and the existing relations for fixed-base structures [18,19]. The results of this comparison are shown in Fig. 5.

The experimentally derived R_y-μ-T_n relations are in very good agreement with the analytically derived R_y-μ-T_n relations for γ_m=0.2. The proposed trilinear relations for γ_m=0.9 indicate the use of lower R_y values compared to the experimentally derived values for the same ductility demand μ, thus leading to conservative seismic design and evaluation of inelastic base-isolated structures. The existing relations for fixed-base structures [18,19] indicate higher R_y values for these structures in comparison with the experimental results. Therefore, the R_y-μ-T_n relations for fixed-base structures are unconservative and cannot be used for the design and evaluation of base-isolated superstructures.

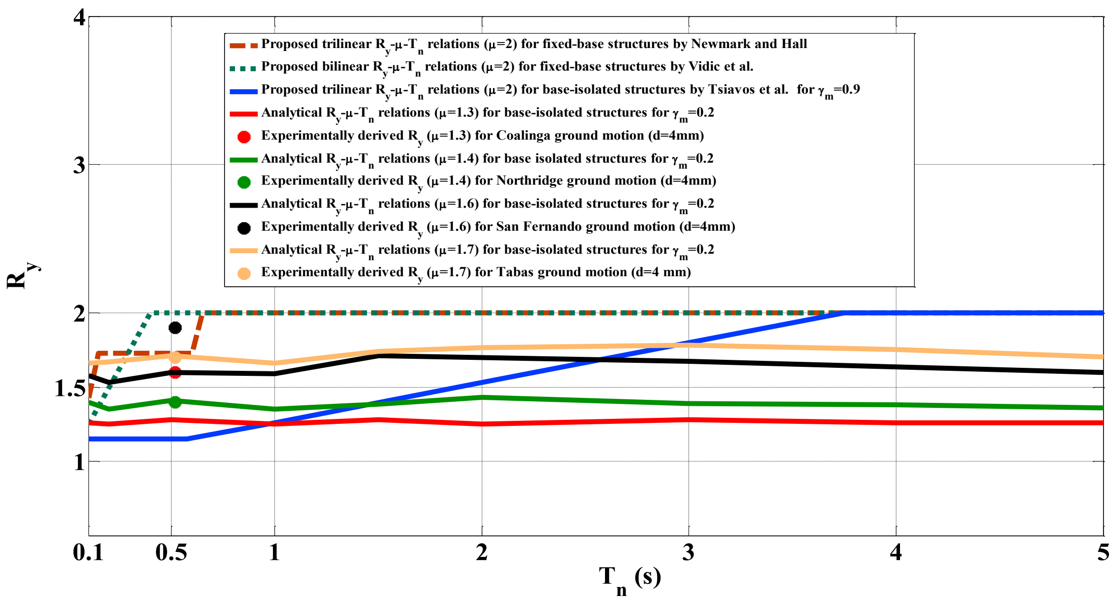

Fig. 5. Comparison of the analytically and experimentally derived R_y-μ-T_n relations

4. Conclusions

This study investigated analytically and experimentally the inelastic behavior of a designed base-isolated structure. The base-isolated superstructure exhibited significant inelastic behavior when subjected to the selected ground motion excitations, thus showing that base-isolated structures can yield due to strong ground motion excitation. This experimentally observed inelastic response of base-isolated structures verified the results obtained through the analytical simulation of these structures.

The differences between the experimentally and the analytically derived time history response of the isolation systemare attributed to the high value of stiction of the bearings, which delayed the activation of the isolation system. Considering the isolated superstructure, the existence of an air gap in the hinge has led to unintended shear deformation of the steel coupons. This shear deformation of the coupons is the main reason for the discrepancies between the analytically and experimentally derived time history responses of the isolated superstructure.

The experimentally determined R_y-μ-T_n relations for base-isolated superstructures verify the analytically derived ones proposed by Tsiavos et al. [20]. It is notable that the R_y-μ-T_n relations for fixed-base structures are unconservative for base-isolated superstructures and cannot be used neither for the seismic design nor for the seismic evaluation of these superstructures. The relations proposed by Tsiavos et al. [20] should be used instead.

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